T_c = Curie temp | T_c = Neel temp

Ferromagnetism | **Ferrimagnetism, Anti-Ferromagnetism**

↑↑↑↑↑ | ↑↓↑↓↑↓↑↓ | ↑↓↑↓↑↓

dipoles = spins = magnetic moments

∃ Net field

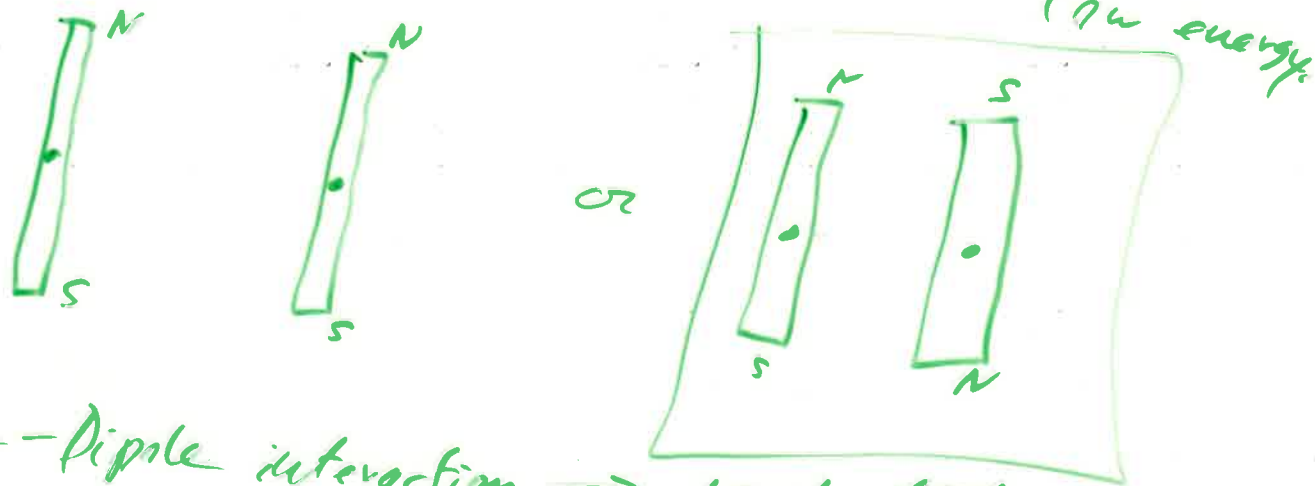
No net field

- Long-range order ~ 10^9 atoms
- phase transitions ← high temp - paramagnetic
  low temp - ferromagnetic
- can form "permanent" magnetic. order exists even if there is no external field. ($H=0$)

Paramagnetism - electrons mainly spins → dipoles, line up only when $H \neq 0$. Ideal paramagnet - dipoles don't influence each other ($Z = z^N$) attractive

Diamagnetism - repulsive. mainly orbital motion (Lenz's Law) = (Faraday's Law)

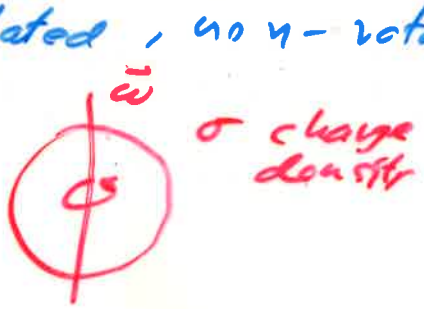
- only exist when $H \neq 0$.



Dipole-Dipole interaction ⇒ nearby dipoles should be anti-parallel.

Magnetism (all kinds) is quantum mechanical in nature.

Niels Bohr (PhD thesis) - Bohr-van Leeuwen theorem
isolated, non-rotating systems



$\vec{F} = q(\vec{E} + v \times \vec{B})$; $U = \int \vec{F} \cdot d\vec{r}$ = does not depend on $\vec{B}$

Q.M — ① Spin - intrinsic angular momentum of particles ⟹ magnetic dipole moment.

② Pauli Exclusion Principle.

Exchange Interaction Energy >> Dipole - Dipole Interaction Energy.

Lenz-Ising Model — Ernst Ising 1920's
Student of Wilhelm Lenz.

One-dimensional — easy.

Two-dimensions - square lattice — solved exactly by Lars Onsager.

↑ ↑ ↑ ↓
↓ ↑ ↓ ↓
↑ ↓ ↑ ↓

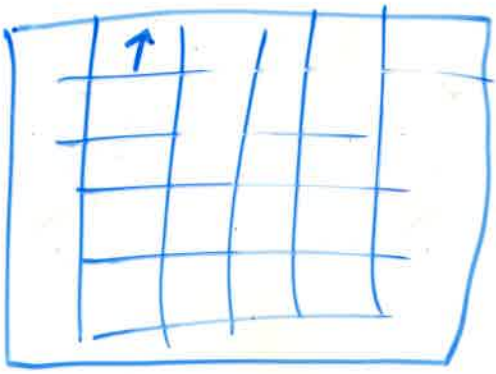
other 2d lattice e.g. hexagonal

⟹ use Mean Field theory.

N dipoles: two states $S_k = +1$ or $S_k = -1$

(no zero)

Problem



100 sites

10×10

configurations $= 2^{100} (2^{10})^{10} \approx (10^3)^{10} = 10^{30}$

$$\frac{10^{30}}{10^9 \cdot 10^3/\text{sec}} = \frac{10^{18}\ \text{second}}{3 \times 10^7\ \text{sec/yr}} \approx 3 \times 10^{10}\ \text{yr}$$

30 billion years! ~ 2× Age of Universe!